Hollow Optical Fiber Bundles for High-Peak Power Transmission

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論文内容要旨

Hollow Optical Fiber Bundles for High Peak Power Transmission

Lasers have been one of the most popular optical devices and gave rejuvenation to the optical sciences since Maiman showed first ruby laser. They have extensive application areas in communications, computing, data storage, image processing, metrology, lithography, and clinical medicine. One of the most popular use of lasers in industry is *laser processing*. It is the processing of materials using lasers, including old cutting and welding, and new micromachining and lithographic techniques. In addition, medical sciences have been highly involved with laser assisted treatments. Both laser processing and medical applications usually require high power lasers. Flexible transmission of these high powers from source to the work place has been a research area since the invention of laser, as well as laser itself. Different kinds of delivery systems are being employed according to requirements of the applications. Roughly, main parameters of the selection for suitable delivery systems are the wavelength of the laser source and energy level that should be delivered to the target. Most common systems include silica or other kind of glass and crystalline fibers, hollow-core waveguides and articulated arms.

Silica fibers are as popular and highly demanded in laser processing applications, as they are in telecommunications, because of the high flexibility. But drawbacks, such as limited transparent bandwidth and low damage threshold of glasses lead the scientists to search other kind of delivery mediums for high-power laser applications. For example at the wavelength of CO_2 laser, $\lambda = 10.6\ \mu m$, silica glasses are not transparent, and hollow glass waveguides have been intensively studied for delivery of this industrial and medical laser. Main advantages of the hollow fibers are low absorption coefficient of air even at high energy levels, which gives permission to the transmission of very high powers, and broad transparent bandwidth, which provides transmission at the wavelengths where glass fibers are not transparent. General structure of a hollow fiber is shown in Figure 1 (left). Smooth metal film coated on the inner surface of a thin-wall glass tube results in low-loss delivery of laser beams.

In this thesis we studied the special use of hollow-glass fibers; we bundled many fibers to use them for laser energy delivery. Until now, hollow fibers have been used as single fibers, together with a lens that focuses the light from source to the core of the fiber. This focusing brings difficulties, which can be summarized as follows,

- At the focused point, air-breakdown may occur for high power applications, and this limits the transmittable power.
- Since there is a focused point, alignment of the fiber is too sensitive. Small misalignment at the input-end can cause high fluctuations at the output power, and also may damage the input-end wall of the fiber.
- At the focused spot and inside the hollow core, energy density is very high, and so damage threshold of the fiber itself limits the transmittable energy.

To address these problems, we propose fiber bundles for laser power delivery. Bundle is directly exposed to the laser beam. In Figure 2 (right) coupling schemes for a single fiber and a fiber bundle are shown. Advantages of the bundle and parallel source beam are as follows,

- Since there is no focused point we expect no air-breakdown
- High alignment tolerance is expected, because of large input-end area of the bundle and parallel source beam.
- High damage threshold is expected, because energy is shared among the fibers.

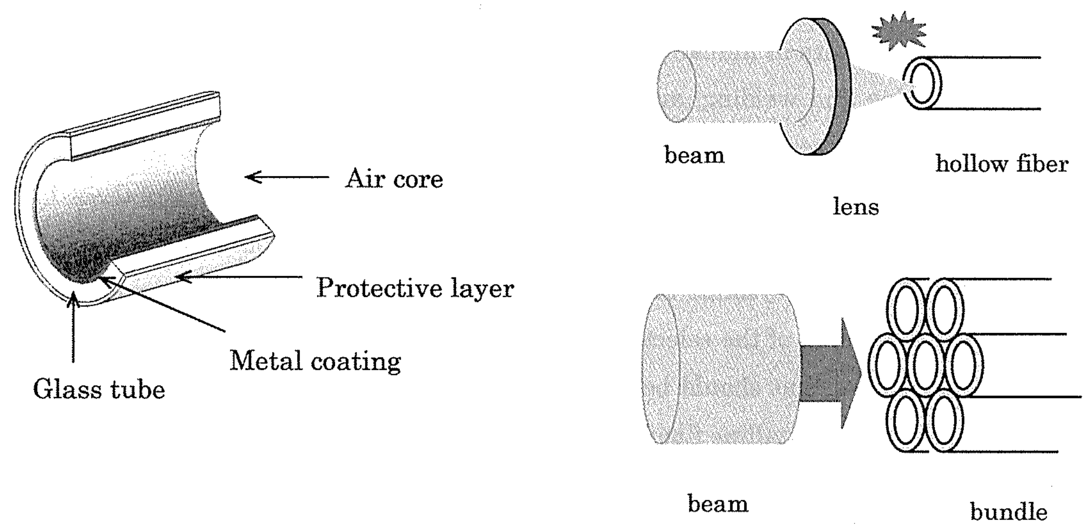

Fig. 1 General structure of a hollow fiber (left) Coupling schemes for a single hollow fiber and a hollow fiber bundle (right)

We developed aluminum hollow fiber bundles for delivery of ArF (λ = 193 nm) and silver hollow fiber bundles for delivery of Q-switched Nd:YAG lasers at second-harmonics (λ = 532 nm) and fundamental mode (λ = 1064 nm). Specifically we aimed delivery of ~50 MW peak power Q-switched Nd:YAG laser pulses for dermatologic applications.

Conventional silica fibers are not transparent at the wavelength of ArF laser. Problem of a single hollow fiber is generation of ozone at the focused spot and inside the hollow core, due to the high energy density. Therefore a complex gas-purging and coupling attachment, which causes additional losses and difficulties at beam-alignment, is definitely necessary. We used an aluminum hollow-fiber bundle to deliver the ArF laser light. Bundle is composed of 40 hollow fibers each with an inner diameter of 0.7 mm. Length is 1 m. First 10 cm of the fibers are molded in an epoxy resin and the rest are bundled by loose plastic sleeves to maintain flexibility. Rectangular input-end of the bundle has the same dimensions with the source beam. Even though energy density is low at this scheme, we observed ozone generation and an increase in the loss during preliminary experiments. Therefore we installed a simple

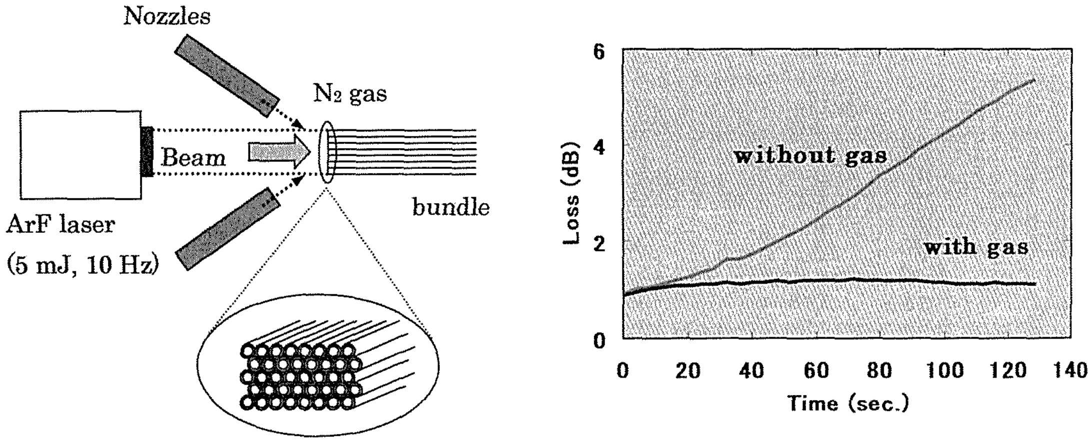

Fig. 2 Experiment setup (left) Measured transmission loss as a function of radiation time (right)

nozzle-configuration to prevent the ozone generation inside the hollow cores. Figure 2 shows the experiment setup and transmission loss of the bundle as a function of time, with-gas and without-gas. Inevitable coupling loss of 2.5 dB caused by wall-thickness and interstitial spaces between circular fibers are not included in the losses in Figure 2. With gas flow, loss is stable and as low as 1.2 dB/m.

Since hollow fibers show additional losses at bent positions, we measured bending losses of the bundle. We could bend it up to a bending radius of R=80 cm. Bundle showed greater bending losses than a single fiber. This is because localized sharp bending in the bundle because of high stress, but this may be prevented by using lubricant between fibers. We also measured misalignment losses of a single fiber and a bundle, when misalignment is intentionally added at the input-ends. Bundle showed greater tolerances to the misalignment, since it has larger area at the input-end, and the source beam is parallel at the coupling point.

For delivery of Q-switched Nd:YAG lasers we developed silver hollow fiber bundles. Conventional silica fibers are highly transparent and well-developed at second-harmonic (λ = 532 nm) and fundamental-mode (λ = 1064 nm) of the continuous wave Nd:YAG lasers. High peak powers caused by Q-switching prevent the use of these silica fibers for Q-switched Nd:YAG lasers. For single hollow fibers transmitted energy is still limited due to low damage threshold. Therefore both kinds of fibers have limited transmitted energy levels because of damage threshold of the materials inside the fibers. We developed silver-coated hollow-glass fiber-bundles to transmit higher energy levels. We used the same method as aluminum fiber bundles. First 20 cm of the fibers are molded in an epoxy resin and remaining parts are bundled using loose plastic sleeves. Length is 80 cm. Bundle is composed of 37-fibers each with an inner diameter of 0.7 mm. We chose the number of fibers as, since in this case, bundle has fairly good flexibility and fairly low energy density inside the fibers. We chose 0.7-mm fibers among available bore-sizes since it gives highest effective area ratio. We also designed a beam-resizing optics to scale the size of source beam to the diameter of the bundle. Experiment setup, and bending losses of the bundle together with bending losses of a single fiber are shown in Figure 3. A circular source beam with diameter of 4.6 mm and divergence angle of 1 mrad at second-harmonic radiation (λ = 532 nm) is launched into the fibers. Bundle shows smaller losses since parallel beam excites low-order modes inside

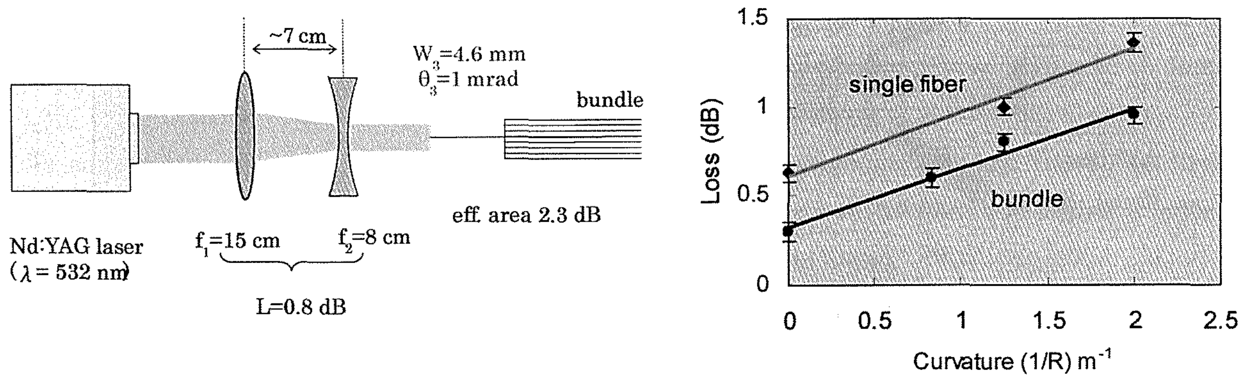

Fig. 3 Experiment setup (left) Bending losses of bundle and a single fiber (right)

fibers. At this wavelength, maximum energy of our laser is 230 mJ and we observed 105 mJ-output-energy (17 MW peak-power @6 nsec), without any catastrophic damages in the fibers. We also measured the output-beam from the bundle and we observed top-hat beam profiles even at bent positions. This may be an important property since material-processing applications require high-quality beams.

To test the damage threshold of the bundle we changed the source to the fundamental-mode. At fundamental-mode our laser has a maximum energy of 450 mJ. When the bundle is directly exposed to the laser beam, we observed no damage, and no change in the loss, up to input energy of ~350 mJ. But greater input energies than 350 mJ, we observed two kinds of damages in Ag-coatings. One is at the input-end and the other is in the middle parts of the fibers. High energy pulses directly ablate the input-end walls and causes damages at the input-end. Debris caused by this ablation goes through the hollow cores and strike of laser to this debris causes the damages inner side of the fibers. Hence we decided damage threshold energy density as 1.7 J/cm^2 and power density as 0.3 GW/cm^2. To protect the bundle we proposed an input-metallization to reflect back the light striking to the silica walls, and a gas-flow to take the debris out of hollow cores. We coated a metal-layer at the input-end of the bundles by sputtering process. Even though this layer protects the bundle, it is so weak that it is also ablated at higher energy levels and exposure times. Secondly we tried a gas-flow scheme as shown in Figure 4, together with a 30-cm bundle. Output-energy as a function of input energy is also shown in Figure 4. Up to input-energy of 300 mJ, output energy is the same for both with-gas and without-gas scheme. But after then output energy shows even decrease for increasing input power in without-gas scheme. With gas-flow we observed ~200 mJ output energy at @6 nsec without damage, corresponding 33 MW peak-power. Maximum recorded value for single hollow fibers (1 mm inner diameter) is 160 mJ @9 nsec, 17 MW peak-power(λ = 1064 nm), and for silica fibers (1.5 mm inner diameter) is 100 mJ @5 nsec, 20 MW peak-power (λ = 532 nm).

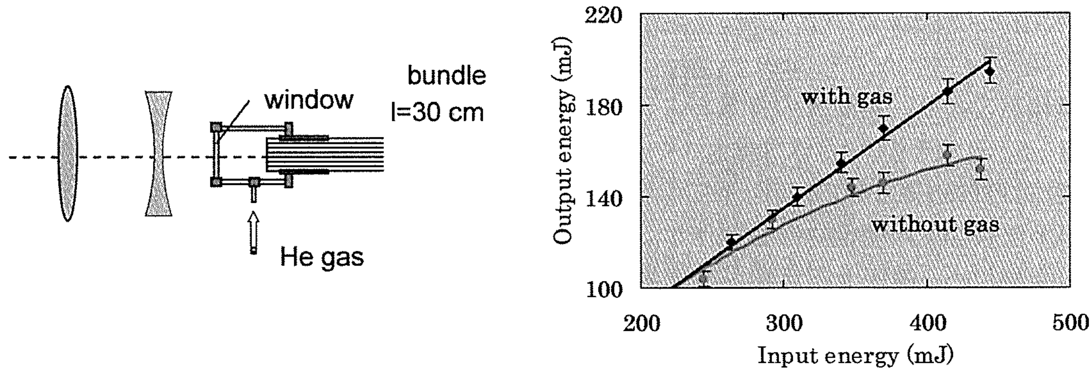

Fig. 4 Gas-introducing attachment (left) Output energy as a function of input energy (right)

One of the disadvantages of bundles is the limited open core-area at the input-end. We called the ratio of this open-area to the total area of the bundle as effective area ratio, and it is currently around 60% for our bundles. We also made an experiment using pure silica fibers and showed that this effective area can be increased to 80% at the wall-thickness of 40 µm, by melting the input-ends of circular fibers. As future works, to increase the effective area is an important point since low effective area severely decreases the transmitted energy level.

Stronger protection is needed at the input-end to prevent the ablation of walls. A metal-cap patterned with the same geometry as the input-end may be a solution.

Also we did not concentrate too much on output beam profiles, which have importance for material-processing applications. Bundle had no quality-degradation in focused beams even at bent positions. But further analysis is still needed on modal properties and output beam profiles of bundles.

論文審査結果の要旨

高ピークパワーを有する短パルスレーザは，産業・医療分野において広く普及しつつある。しかし，通常の石英ガラス光ファイバは，紫外域における材料吸収や，材料の光学的非線形性に起因する自己集光効果が問題となり，紫外から赤外領域の高ピークパワー光パルス伝送には適さない。また,単一の中空ファイバは，材料吸収や非線形性の問題が生じないものの，伝送パワーが中空コアに集中するため，絶縁破壊や吸収性ガスの生成などの問題が生じる。そこで著者は，複数の中空ファイバを束ねた光伝送路を構成することにより，光電力密度を低く抑えて，紫外，可視，赤外のナノ秒高ピークパワー光パルス伝送が可能なバンドル型中空ファイバを実現した。本論文はその研究成果をまとめたもので，全編5章よりなる。

第1章は緒言であり，本研究の背景および目的について述べている。

第2章では，波長193nmのArFエキシマレーザ光パルス伝送を目的として，アルミニウム中空光ファイバを用いたバンドル型伝送路を製作し，その評価を行っている。伝送路内の光電力密度を低く抑えることが可能なため，簡便な不活性ガス導入機構を用いるだけで，紫外光を吸収するオゾンの発生を防止できる。これはエキシマレーザ用伝送システムの構築を容易にする有用な成果である。

第3章では, 高いアブレーション効率を有する波長532nmのQスイッチNd:YAGレーザ第2高調波光パルス用伝送路を３７本の銀中空ファイバをバンドル化したものにより構成し，その評価を行っている。長さ1mの伝送路において，伝送損失1.2dBという低損失伝送が達成され，単一の中空光ファイバと比較して，光学アライメントのずれに対して高い許容性を示すことを明らかにしている。

第4章では，バンドル型中空ファイバの高ピークパワー光パルス伝送時の耐久性を評価するために, 波長1064nmのQスイッチNd:YAGレーザ基本波を用いた実験を行っている。これにより，バンドル型銀中空ファイバによりピークパワー33MWの光パルスを安定して伝送可能であることを示している。これは従来の石英ガラス光ファイバや単一の中空ファイバと比較して，飛躍的に高いパワーである。また，入射レーザ光に対する開口率を高くする手法についても検討している。

第5章は結言であり，各章の成果をまとめている。

以上要するに本論文は，高ピークパワーをもつレーザ短パルス光の伝送路として，バンドル型中空ファイバを提案し，実験に基づく検証によりその伝送特性を明らかにするとともに，高効率かつ高い耐久性を有する伝送路の実現についての有用な知見を与えたもので，光伝送工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。